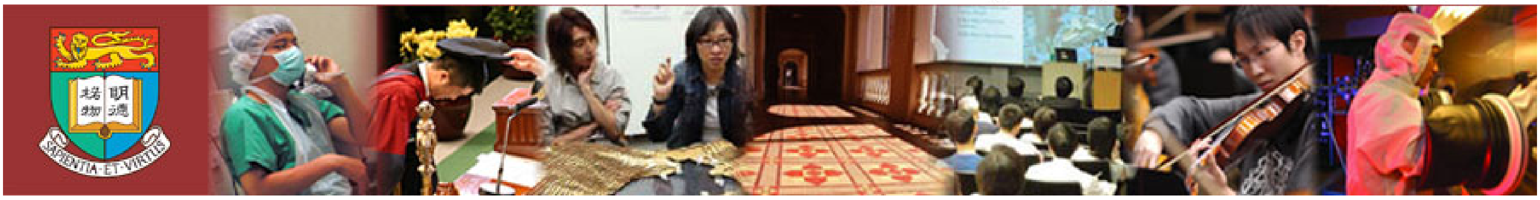

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Citation	**Journal of Lightwave Technology, 2008, v. 26 n. 23, p. 3770-3775**
Issued Date	**2008**
URL	**http://hdl.handle.net/10722/92156**
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All-Optical Tunable Delay With NRZ-to-RZ Format Conversion Capability Based on Optical Kerr Switch and Pulse Pre-Chirping

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***Abstract*—All-optical tunable delay plays an important role for enabling high-throughput optical routing, such as buffer for contention resolution and timing synchronization. We proposed and demonstrated a widely tunable optical delay using optical Kerr-switch-based wavelength converter and pulse pre-chirping for compensating chromatic dispersion in fiber delay. With wideband operation provided by a Kerr-switch wavelength converter, a tunable delay range up to 8.56 ns was achieved. Meanwhile, pulse pre-chirping helped to alleviate group-velocity dispersion (GVD)-induced penalty, and provided simultaneous nonreturn-zero (NRZ)-to-RZ format conversion functionality.**

***Index Terms*—Cross-polarization modulation, dispersion compensation, optical delay.**

I. Introduction

IN THE context of optical signal processing, optically controllable tunable delay has been an important aspect for its significant in enabling all-optical routing and packet processing in optical network, and for phase control and beam forming in photonic microwave signal processing [1], [2]. In particular, fiber-based techniques have additional advantages due to the availability of low-cost components. Previously, fiber-based delay devices have been realized by using gain-induced group-velocity modulation based on Brillouin [3], Raman [4] and optical parametric process [5], [6]. However, these approaches rely on steep gain slope and induced dispersion of the amplifiers and thus would result in severe pulse distortion [7]. Another design philosophy aiming to increase usable delay of the device is to combine the group velocity dependency on wavelength of highly dispersive fiber and wavelength conversion techniques, such as self-phase modulation (SPM) [8] and idler generation in optical parametric process [9]–[13]. Unfortunately for SPM-based device, its performance depends on the wavelength detune of converted signal from the input signal and extensive pulse broadening could prohibit its use in large delay; for OPA-based device, the input wavelength range could be limited due to stringent phase-matching condition.

In order to achieve large delay over wideband, a wavelength-insensitive approach with robustness to group-velocity dispersion (GVD) would be desirable. An optical tunable delay using optical Kerr switch for wavelength conversion and pulse pre-chirp to combat for GVD-induced distortion would be promising under these considerations [14]. Thanks to regenerative nature of Kerr switch, this approach can help to reduce pattern-dependent amplitude fluctuation due to GVD and can be used to implement wideband large delay device. Furthermore, pulse pre-chirping can be used to perform nonreturn-zero (NRZ) to return-zero (RZ) conversion through pulse compression effect [15]. As RZ format has been widely used owing to its robustness to nonlinear effect-induced signal degradation such as four-wave mixing effect in transmission fibers and optical parametric amplifiers [16]–[18], an optical delay with format conversion functionality would be desirable for use in synchronizing and bridging short-haul NRZ bit stream to RZ bit stream in long-haul links.

In this paper, we present a comprehensive study on the theory and performance of the optical tunable delay we proposed previously [19]. The organization of this paper is as follow. Section II describes the principle behind the proposed scheme, with emphases on the theory of Kerr switch and pulse pre-chirping. Section III provides details on the experimental setup used to verify the proposed scheme, and discussions on the results obtained. Concluding remark is given in Section IV.

II. Theory of Operation

The operating principle of the proposed optical tunable delay is based on optical Kerr switching for wideband wavelength conversion, and pulse pre-chirping to compensate for the dispersion penalty in fiber, as shown in Fig. 1. The intensity modulation of the incoming signal at λ_s is transferred to a phase-modulated cw probe with arbitrarily chosen wavelength λ_p in the first-stage Kerr switch. The converted probe is then launched to a dispersive fiber. The propagation delay of the probe wave inside the dispersive fiber depends on the wavelength of the probe due to large chromatic dispersion. Therefore, the delay of the probe can be controlled by tuning the wavelength of the probe. The delayed probe was then back converted to signal wavelength (λ_s) in the second-stage Kerr switch. Detailed descriptions are provided in the following sections:

Manuscript received July 29, 2008. Current version published January 28, 2009. This work was supported in part by the Research Grants Council of the Hong Kong Special Administrative Region, China, under Projects HKU 7179/06E and HKU 7172/07E.

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Digital Object Identifier 10.1109/JLT.2008.2004928

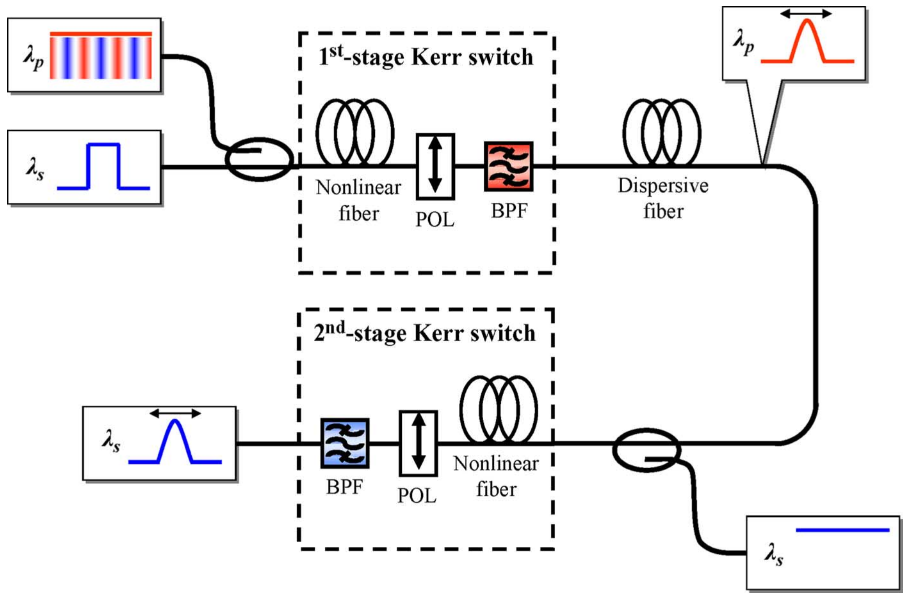

Fig. 1. Principle of Kerr switch-based optical tunable delay. POL: Polarizer; BPF: Bandpass filter. Refer to text for detailed description.

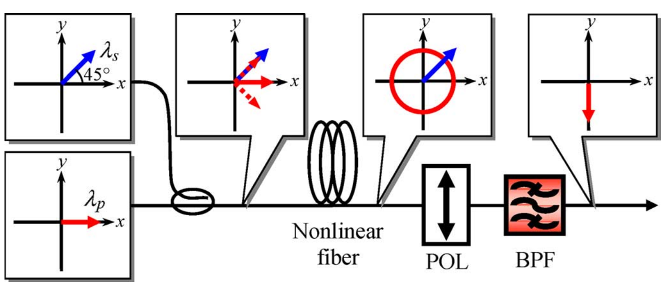

Fig. 2. Principle of Kerr switch based wavelength converter. The transmission axis of the polarizar (POL) is along y axis in the polarization chart.

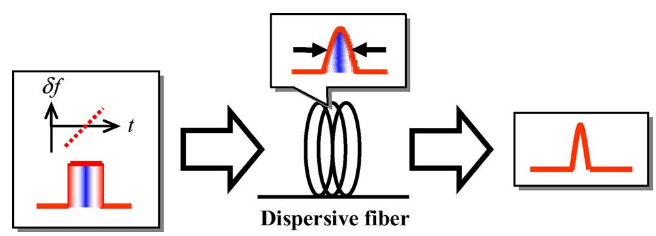

Fig. 3. Principle of GVD-compensation by pulse pre-chirping.

A. Optical Kerr-Switch-Based Wavelength Conversion

The wavelength converters in the proposed tunable delay are based on cross-polarization modulation (XPolM) in nonlinear medium. Each stage of the Kerr switch, as shown in Fig. 2, consists of a spool of nonlinear fiber for XPolM, a polarizer to convert polarization modulation to intensity modulation, and a bandpass filter to eliminate the control lightwave. At the fiber input, the intensity-modulated signal (λ_s) serves as the control, which its modulation is to be transferred to another wavelength designated by a cw probe (λ_p). Note that the state of polarizations (SOPs) of the input control and probe are assumed to be linear for simplicity. The SOP of the input probe is adjusted to be either orthogonal or parallel to the transmission axis of the polarizer, corresponding to noninverting or inverting mode of operation of the Kerr switch. On the other hand, the SOP of the control signal is rotated from that of probe by 45°. When the probe co-propagates in the nonlinear fiber, the high intensity control pulse will cause phase shift of the probe component parallel to the control due to optical Kerr effect [14], [20]. As a result, the SOP of the probe is rotated and therefore part of its energy can pass through the polarizer. Assume the power of the probe is weak so that the polarization of the control signal is not affected by the Kerr effect due to probe wave, and other nonlinear effect is negligible, the transmitted power P_P of probe wave is governed by the following function [20]:

$$P_P = P_{P0}\sin^2\left(\frac{2}{3}\gamma P_s L\right) \tag{1}$$

where γ and L are the nonlinear coefficient and length of the fiber, and P_s is the power of the control signal respectively. From (1), if the contrast of the control signal is large enough and the power level of the mark level is close to $3\pi/4\gamma L$, the intensity noise on the control signal will be suppressed when the intensity modulation is transferred to probe. It gives rise to regenerative effect of a Kerr switch.

B. Pulse Pre-Chirp for Dispersion Compensation

Although Kerr switch wavelength conversion helps to achieve large delay range with its wideband operation, dispersion-incurred penalty of the converted signal is unavoidable without special care due to its nonphase-preserving nature. To compensate for the dispersive effect, a simple pulse pre-chirp technique is deployed in this proposed scheme. Fig. 3 illustrates the principle of the pre-chirping technique. Instead of launching an unmodulated probe, the cw probe is phase-modulated with a periodic parabolic signal which is synchronized to the incoming bit stream. The parabolic phase profile of the probe wave generates a linear frequency chirp. When the chirped probe wave

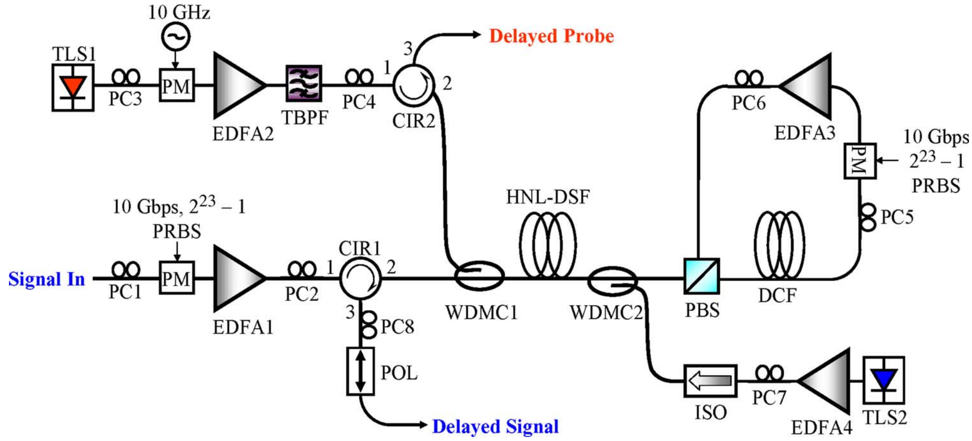

Fig. 4. Experimental setup of the proposed delay line. Refer to the text for detailed description.

propagates through fiber with large dispersion, the frequency chirp causes the pulse to be compressed temporally [15], [21]. In effect GVD-induced pulse broadening can be minimized, and at the same time, the pulse compression converts the format of the signal from NRZ to RZ. However, a parabolic signal occupies infinitely large bandwidth as it is discontinuous at the bit slot boundary, and therefore it is unrealizable in practice. Here we adopt a sinusoidal pre-chirping waveform which the trough of the waveform is aligned to the center of the bit slot. With even-symmetric phase profile, the frequency chirp is quasi-linear about the bit slot center and thereby is useful for GVD-compensation.

Note that the bit rate supported by the pre-chirp scheme depends on the total dispersion in the optical delay. Using the empirical formula provided in [21], one can deduce that the bit rate B scales with total dispersion D and RZ duty ratio as follow:

$$33\%\ \text{duty ratio}: \ B \approx 0.279\sqrt{\frac{2\pi c}{\lambda^2|D|}} \tag{2}$$

$$50\%\ \text{duty ratio}: \ B \approx 0.54\sqrt{\frac{2\pi c}{\lambda^2|D|}}. \tag{3}$$

III. Experiment and Discussions

The experimental setup of the proposed optical tunable delay and format converter is shown in Fig. 4. In the first stage Kerr switch, the incoming NRZ signal at 1570 nm with intensity modulation carrying 10 Gb/s $2^{31}-1$ pseudorandom binary sequence (PRBS) was phase-modulated with 10 Gb/s $2^{23}-1$ PRBS for stimulated Brillouin scattering (SBS) suppression in fibers. Note that SBS suppression through phase modulation can be avoided by using fiber with high nonlinearity and SBS threshold such as bismuth-oxide fiber [22].The probe wave, on the other hand, was generated by a tunable laser source TLS1 and phase-modulated by 10 GHz sinusoidal signal synchronized to the bit stream of the signal. The phase-modulated signal and probe were then amplified to 19 dBm and 13 dBm, respectively, and combined using a WDM band coupler (WDMC1). The combined lightwaves were launched into a spool of 1 km highly-nonlinear dispersion-shifted fiber

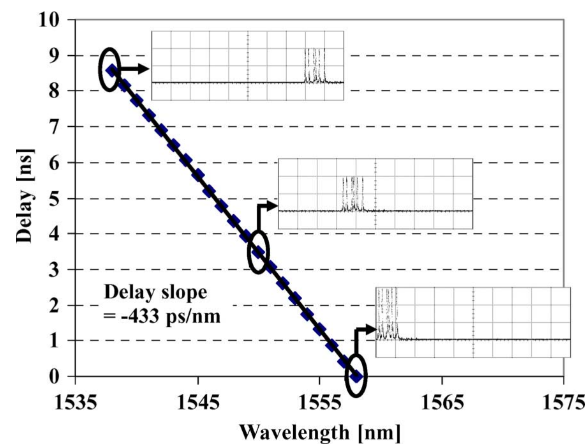

Fig. 5. Measured delay of output signal versus probe wavelength. Insets show the waveform of output signal with an input packet carrying bit pattern [101001101001]. Horizontal scale of the insets is 1.1 ns/div.

(HNL-DSF) with nonlinear coefficient $\gamma = 14\ /\mathrm{W/km}$, zero-dispersion wavelength $\lambda_0 = 1560$ nm and dispersion slope $dD/d\lambda = 0.035\ \mathrm{ps/nm^2km}$. After XPolM in HNL-DSF, the signal and probe were decoupled using another WDM band coupler (WDMC2). The probe wave polarized by a polarization beam splitter (PBS) was launched into a spool of dispersion compensating fiber (DCF) with total dispersion of -433 ps/nm. After passing through DCF, the probe was phase dithered by 10 Gb/s $2^{23}-1$ PRBS to suppress SBS in HNL-DSF, and amplified to 22 dBm by EDFA3. The amplified probe was coupled back to WDMC2 together with the amplified CW signal at 1570 nm from TLS2 and then launched back into HNL-DSF for second-stage Kerr switch. The delayed signal was then retrieved at port 3 of signal circulator CIR1, polarized using polarizer POL and monitored through a digital communication analyzer (DCA) or a bit-error rate tester (BERT).

Fig. 5 shows the measured delay of the output signal against the wavelength of the probe wave. The delay of the output signal is measured relative to the minimum delay of the output signal, which is obtained when probe wavelength is 1558 nm. From the plot, the delay of the output signal varies linearly with the probe wavelength, with slope equals to the total dispersion of the DCF used ($D \approx -433\ \mathrm{ps/nm}$). The maximum delay attained

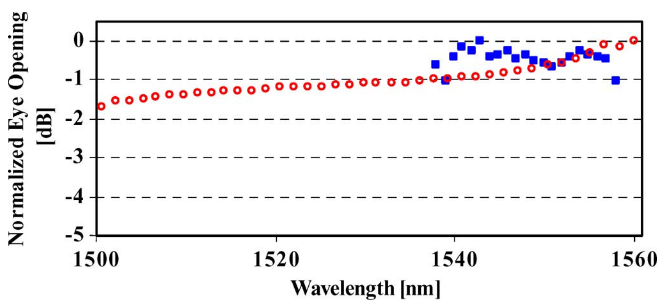

Fig. 6. Simulated (red circle) and experimental (blue square) eye opening of the converted probe. The eye opening values are normalized to the maxima of the respective data sets.

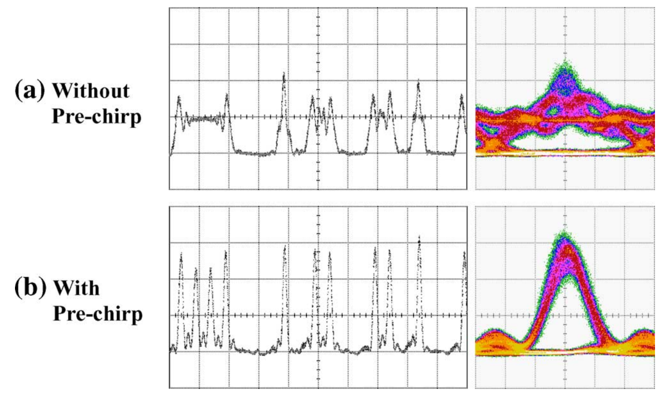

Fig. 7. Waveforms and eye diagrams of output probe when pre-chirp signal is (a) turned off and (b) turned on. Horizontal scales are 200 ps/div for waveforms and 20 ps/div for eye diagrams.

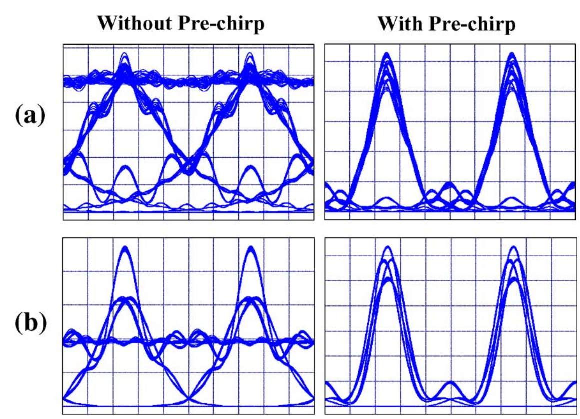

Fig. 8. Simulated eye diagrams of output probe with (a) noninverting and (b) inverting Kerr switches. Horizontal scale is 20 ps/div.

is 8.56 ns when probe is at 1538 nm. The delay is limited by the gain bandwidth of the C-band EDFA (1538 nm–1565 nm). To examine the feasible wavelength range of the Kerr switch wavelength converter, a simulation was done using the same conditions as in the experiment. Fig. 6 shows the simulated and experimental eye opening (in decibel) of the converted probe. The eye opening is defined as the voltage difference between the minimum mark level and maximum space level for simulated result, or between three standard deviation down from mean mark level and up from mean space level for experimental result. From the simulation, the degradation of eye opening is within 2 dB for probe wavelength from 1500 nm to 1560 nm. The degradation at the short wavelength end is due to walk-off of the signal from the probe in the HNL-DSF. Such degradation can be mitigated using dispersion-flattened nonlinear fiber, which enables wavelength conversion over 120 nm bandwidth [14]. This means delay range can be extended by simply replacing the probe amplifiers with wide band substitutes such as hybrid S/C-band EDFAs.

Fig. 7 shows the waveforms and the eye diagrams of the probe signal obtained at port 3 of the circulator in signal path obtained in experiment. When the pre-chirping signal is turned off, severe pulse distortion is observed from both the waveform and the eye diagram, where the mark level is hardly defined. It is noticeable that spikes are present at the pulse edges. The eye distortion and the presence of spike at pulse edges are due to GVD in fiber and residue phase modulation of the probe after XPolM. Given a normal dispersive fiber, optical pulse propagating along would usually experience pulse broadening even with SPM [20]. However, if the optical pulse is generated by a Kerr switch operating in inverting mode, the chirp induced on the pulse will be reverse of SPM-induced chirp as the chirp generated by a rising edge of the control pulse in Kerr switch will be transferred to the corresponding falling edge of the converted pulse. Fig. 8 shows the simulated waveforms of a Kerr switch-converted signal operating in inverting and noninverting modes. It is clear that while the signal pulse obtained from inverting Kerr switch contains spikes at the edges, the signal from noninverting Kerr switch suffers from severe ISI due to pulse broadening. As will be discussed later, operating the Kerr switch in inverting mode can improve the signal quality with pre-chirp.

By engaging pre-chirp, intensity fluctuation in mark level of probe signal eye is greatly suppressed as observable from Fig. 7. Quantitatively, the eye signal-to-noise ratio of the pulse is improved by 10 dB. With strong chirp induced by pre-chirping technique, the weaker residue chirp due to XPM effect in Kerr switch is overridden. Therefore, each bit slot contains approximately equal amount of chirp. After the DCF, the probe pulse is compressed which the compressed pulse shape is determined by the chirp of the original pulse. As the amount of chirp is equal among the pulse, the pulse shape becomes approximately equal, and therefore results in intensity fluctuation reduction as in Fig. 7 and 8. When the eye of pre-chirped probe wave from inverting and noninverting converter is compared, intensity variation at mark and space level is greater for noninverting converter. This is because the residue chirp on the noninverting probe enhances the pulse broadening effect in the DCF with normal dispersion. The excessive pulse broadening renders the sinusoidal chirp on the probe wave inefficient for GVD compensation as the broadened pulse extends beyond the linear chirp region of the pulse. Therefore, ghost pulse is observable in the space level of the noninverting probe even with pre-chirp engaged.

In addition to intensity noise reduction, the intensity modulation of the probe wave is converted to RZ format with 30% duty cycle after the pre-chirp signal is turned on. However, pedestal pulse is clearly observed between the main pulses. The presence of pedestal pulse is caused by deviation of pre-chirping signal

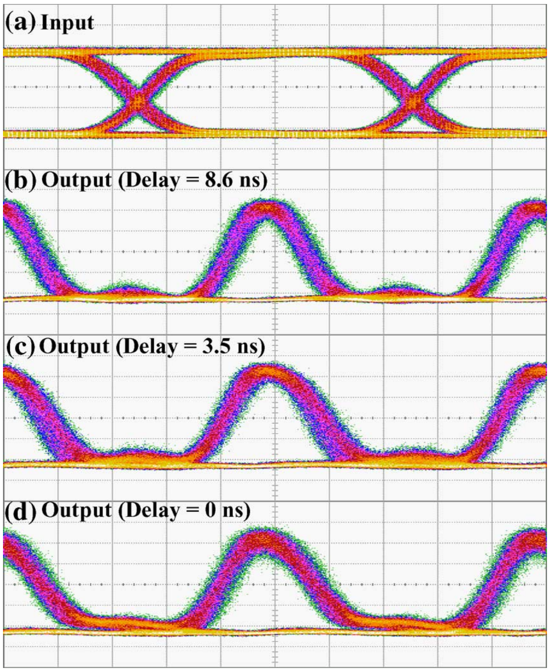

Fig. 9. Eye diagrams of input and output signal at different relative delay. Horizontal scale is 20 ps/div.

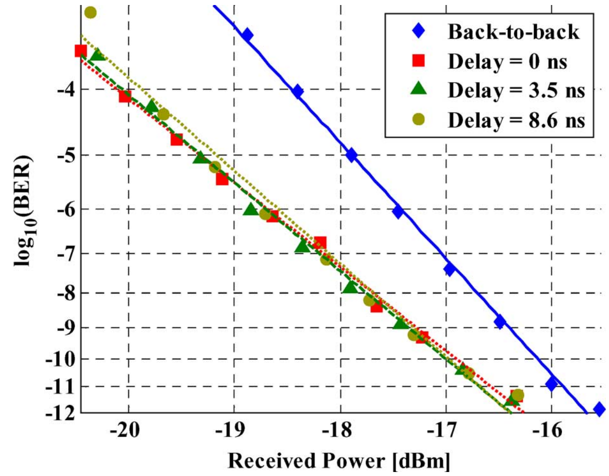

Fig. 10. BER plots of input signal, and delayed signal with 8.56 ns, 3.5 ns and 0 ns relative delay.

used from the ideal one. Although linear chirp around the bit slot center is helpful in compensating second-order dispersion, the nonlinear chirp near to the bit slot emulates higher-order dispersion, which generates trailing pulses at both edges.

Fig. 9 shows the eye diagrams of the input NRZ signal, and the delayed RZ signal at port 3 of the circulator in signal path obtained in experiment. From the eye diagrams, clear eye opening is obtained throughout the delay range provided by the tunable delay. Thanks to the limiting transfer characteristic of the Kerr switch around the maximum transmission regime, the residue intensity modulation is suppressed to an unobservable level. The SNRs and extinction ratio of the output signals are over 21 dB and 15 dB, which is comparable to or even surpass those of the input signal (25 dB and 13 dB respectively). Pedestal pulses are seen between adjacent signal pulses, which are inherited from the delayed probe wave. We believe the pedestal pulses can be eliminated by using common pedestal suppression techniques [23], [24]. Moreover, the pre-chirp conditions can be modified to achieve pedestal-free compression using the condition given in [21].

Fig. 10 shows the bit-error rate (BER) plot of the delayed RZ signals and the input NRZ signal. From the plot, error-free operation is achieved over the whole delay range provided by the tunable delay. The delayed signals have an uniform power penalty of -1 dB at $\text{BER} = 10^{-9}$. The apparent enhancement of receiver sensitivity of the delayed signals is due to difference in duty cycle between NRZ and RZ format, as RZ signal pulse has higher peak power when compared to its NRZ counterparts at the same average power level. With the difference in peak power level taken into account, the power penalty incurred by the tunable delay is 1.6 dB referencing to the typical sensitivity gain of 2.6 dB for 33% duty ratio RZ format [25]. The reduction of negative power penalty from typical sensitivity gain is believed to be caused by three factors. Firstly, as the use of optical filters is kept minimal in the experimental setup, the excess ASE noise from EDFAs unavoidably affects the quality of the delayed probe and signal. Secondly, the presence of pesdestal pulse effectively decreases the peak power of the signal pulse when comparing to an ideal RZ signal, which results in apparent reduction in receiver sensitivity. Lastly, as the pulse duration of RZ signal is reduced, the adverse effect of timing jitter on receiver sensitivity is magnified. Nevertheless, the experimental results suggested the promising performance of the tunable delay over the whole delay range.

Finally, note that although Kerr switch wavelength converter in its simplest form only works with intensity-modulated signal, modification could be done on the Kerr switches to cope with phase-modulated input signals [26], [27]. This means the proposed scheme could be versatile regarding input signal modulation format.

IV. Conclusion

We have demonstrated an optical delay with NRZ-RZ format conversion functionality based on optical Kerr switching and pulse pre-chirping technique. The wideband operating range of the Kerr switch wavelength converter enabled large delay tunable range up to 8.56 ns. Meanwhile, limiting power transfer characteristic at maximum transmission regime of the Kerr switch helps to reduce the intensity fluctuation induced by GVD effect. To compensate GVD in fiber, pulse pre-chirp is deployed using phase modulation with sinusoidal signal, which also provides simultaneous NRZ-to-RZ format conversion functionality. With help from regenerative property of Kerr switch and pulse pre-chirping, -1-dB power penalty is achieved over the whole delay range. Further enhancement could be achieved by using optical amplifiers with larger gain bandwidth to increase tunable delay range, and by deploying simple pedestal removal measure to improve pulse shape.

Acknowledgment

The authors would like to acknowledge Sumitomo Electric Industries for providing the HNL-DSF used in this work.

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